

Nucleation of antikaon condensed matter in proto neutron stars

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Abstract. A first order phase transition from nuclear matter to antikaon condensed matter may proceed through thermal nucleation of a critical droplet of antikaon condensed matter during the early evolution of proto neutron stars (PNS). Droplets of new phase having radii larger than a critical radius would survive and grow, if the latent heat is transported from the droplet surface to the metastable phase. We investigate the effect of shear viscosity on the thermal nucleation time of the droplets of antikaon condensed matter. In this connection we particularly study the contribution of neutrinos in the shear viscosity and nucleation in PNS.

Keywords: Neutron stars, antikaon condensation, nucleation

PACS: 26.60.-c, 97.60.Jd, 05.70.Ce, 82.60.Nh

INTRODUCTION

A first order phase transition from hadronic to exotic matter phases may proceed through the nucleation of droplets of the new phase. The formation of droplets of quark matter [1, 2, 3] and antikaon condensed matter [4, 5] in neutrino-free neutron stars (NS) was studied using the homogeneous nucleation theory of Langer [6]. Droplets of new phase may appear in the metastable nuclear matter due to thermal fluctuations. The droplets of the stable phase with radii larger than a critical radius survives and grows if the latent heat is transported from the surface of the droplet to the metastable state. This heat transportation occurs through thermal dissipation [7] and viscous damping [8].

We have seen that the onset of antikaon condensate influences the shear viscosity of NS matter composed of neutron(n), proton(p), electron(e) and muon(μ) that can interact by strong or electromagnetic interactions [9]. Effect of shear viscosity on the nucleation of the antikaon condensed matter was recently been studied [10] in depletonised NS, after the neutrinos are emitted. Here we investigate the contribution of neutrinos to the shear viscosity and nucleation of antikaon condensates. In the PNS where the temperature is of the order of a few 10s of MeV, neutrinos are trapped because their mean free paths under these conditions are small compared to the radius of the star. On the other hand, they are very effective at transporting both heat and momentum because their mean free paths are orders of magnitude larger than that for other particles.

FORMALISM

We adopt the homogeneous nucleation theory of Langer [6] to calculate the thermal fluctuation rate for a first order phase transition from the charge-neutral and beta-equilibrated nuclear matter to K^- condensed matter in a neutrino-trapped PNS. The thermal nucleation rate is given by

$$I = \Gamma_0 \exp\left(-\frac{\Delta F(R_c)}{T}\right), \quad (1)$$

where ΔF = is the change in free energy required to activate the formation of the critical droplet. $\Gamma_0 = \frac{\kappa}{2\pi} \Omega_0$, is the prefactor of which $\Omega_0 = \frac{2}{3\sqrt{3}} \left(\frac{\sigma}{T}\right)^{3/2} \left(\frac{R_c}{\xi}\right)^4$ is the statistical prefactor and $\kappa = \frac{2\sigma}{R_c^3 (\Delta w)^2} [\lambda T + 2(\frac{4}{3}\eta + \zeta)]$ is the dynamical prefactor. Here σ is the surface tension for the surface separating the two phases, ξ is the correlation length for kaons, Δw is the difference of the enthalpy of the two phases, λ the thermal conductivity, η and ζ are the shear and bulk viscosity respectively. The free energy is maximum at this critical radius given by

$$R_c(T) = \frac{2\sigma}{(P^K - P^N)}. \quad (2)$$

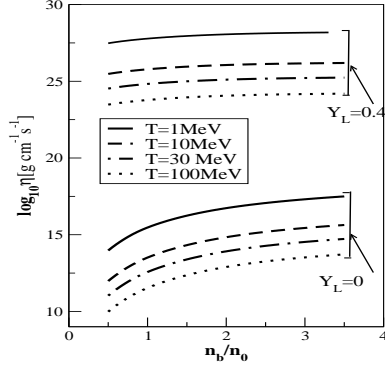


Figure 1: Total shear viscosity in nuclear matter phase is plotted with normalised baryon number density for i) neutrino-free NS ii) neutrino-trapped PNS.

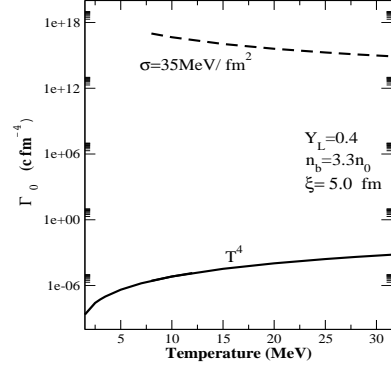


Figure 2: Prefactor as a function of temperature at a fixed density and surface tension for PNS matter .

Finally the thermal nucleation time is given by $\tau_{th} = (V_{nuc}I)^{-1}$, where $V_{nuc} = \frac{4\pi}{3}R_{nuc}^3$ is the volume of the core, where the thermodynamic variables is assumed to remain constant.

To calculate shear viscosity in the PNS, which is mostly contributed by the neutrinos [13], we consider the scattering of neutrinos $\nu_e + N \rightarrow \nu_e + N$ where $N=n, p, e$. Shear viscosity of neutrinos due to scattering is calculated using the coupled Boltzmann transport equation [13]. For the deleptonised NS, total shear viscosity is given by $\eta = \eta_n + \eta_p + \eta_e + \eta_\mu$ as in Ref. [9].

The Model EoS. In order to calculate the shear viscosity and critical radius (R_c), we need to know the EoS, that we construct at finite temperature using the relativistic mean field model [11, 12]. The interaction between baryons is mediated by the exchange of scalar (σ) and vector (ω, ρ) mesons. This picture is consistently extended to include the kaons. We use the parameter sets of GM1 model [14] for nucleon-meson coupling constants. The kaon-meson coupling constants are determined using quark model, isospin counting rule and the real part of K^- potential depth, that we take as -160 MeV in our calculation [9].

Results

The total shear viscosity is shown as a function of normalised baryon density for different temperatures in Fig. 1. We consider two cases i) the deleptonised NS matter, where the total shear viscosity has contribution from all the species such as n, p, e and μ ; ii) for the neutrino-trapped PNS matter (lepton fraction $Y_L = 0.4$), where the major contribution comes from neutrinos. In both the cases shear viscosity decreases with rising temperature.

The prefactor Γ_0 is plotted as a function of temperature for PNS in Fig. 2 and is compared when it is approximated by T^4 from dimensional analysis. Here we find the shear viscosity term changes the prefactor by a large order of magnitude compared to T^4 approximation. This difference is much more pronounced in PNS compared to NS [10].

In Fig. 3 we display the nucleation time as a function of temperature for a set of values of surface tension at a fixed baryon density for lepton-trapped PNS matter and find that both the droplet radii and the thermal nucleation time strongly depend on the surface tension. Nucleation may not occur in PNS for surface tension $< 30 \text{ MeV fm}^{-2}$ as the radius of droplet is less than the correlation length ($\xi \sim 5 \text{ fm}$). We approximate that the radius of the droplet should be greater than ξ in this calculation [5, 7]. For NS case, nucleation is observed to be possible for $\sigma < 20 \text{ MeV fm}^{-2}$ [10]. Larger viscosity there leads to larger value of T which might melt the condensate.

Finally in Fig. 4 we compare the results of thermal nucleation time taking into account the effect of shear viscosity in the prefactor with that of the prefactor approximated by T^4 . For PNS we displayed the results for $n_b = 3.30n_0$ and $\sigma = 35 \text{ MeV fm}^{-2}$. We find the result of the T^4 approximation a few orders of magnitude higher than those of our calculation. These results demonstrate the importance of including the shear viscosity in the prefactor of Eq. (1) in the calculation of thermal nucleation time. We already obtained similar results for NS matter [10]. Also, it may be

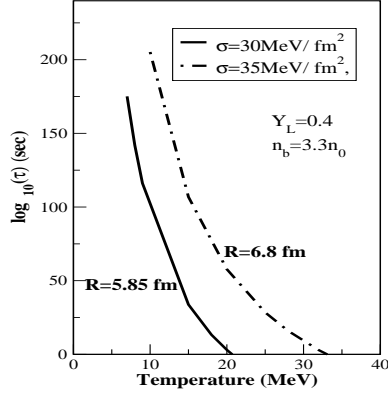


Figure 3: Thermal nucleation time is displayed as a function of temperature for PNS matter .

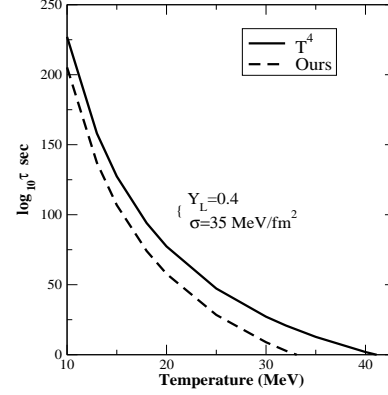


Figure 4: Our result for thermal nucleation time is compared with the calculation of T^4 approximation for PNS.

mentioned that nucleation of antikaon condensates is possible if $\tau_{th} < \tau_{cooling} (\sim 100s)$. That is possible for PNS with $\sigma \geq 30 \text{ MeV fm}^{-2}$.

Summary

We have investigated the role of shear viscosity on the thermal nucleation rate for the formation of a critical droplet of antikaon condensed matter. For this we considered a first order phase transition from the nuclear to antikaon condensed matter in PNS. We have seen that the droplet radii increase with increasing surface tension. We also compare the nucleation times for NS and PNS and found that nucleation is possible for a lower value of surface tension $\sigma < 20 \text{ MeV fm}^{-2}$ in NS while it may be possible only for higher value in PNS ($\sigma \geq 30 \text{ MeV fm}^{-2}$).

ACKNOWLEDGMENTS

S.B. would like to acknowledge the Department of Science & Technology, India for the travel grant to present this paper in the conference PANIC11.

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